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REPORT

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Title:
A preliminary study of Lofoten as a potential World Heritage Site based on natural criteria

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Summary:
The geology of the Lofoten region has been described with the aim of assessing whether or not the area would qualify as a candidate for the World Heritage List based on its natural properties.
The Lofoten archipelago consists mainly of Palaeoproterozoic rocks, including paragneisses and younger plutons (ca 1800 Ma) of the anorthosite–mangerite–charnockite–granite (AMCG) suite. The Precambrian basement of the Lofoten and the adjoining Vesterålen islands is part of a NNE-trending basement high that is overlain to the east by a stack of allochthonous nappes occupying the central axis of the Scandinavian Caledonides.
The unique setting of Lofoten as an exposed ridge of lower crustal rocks forming a basement high on a highly extended continental margin is a result of an exceptional combination of tectonic events and subsequent glacial erosion and weathering. Apart from its breathtaking landscape, the well-exposed Lofoten archipelago provides an exceptional possibility to study the effects of past and present geological processes. The Precambrian rocks along Lofoten are highly resistant to erosion. Although they are substantially modified, the chain of mountainous islands persisted during extended periods of severe glacial conditions. The present 'Alpine' landforms are governed by a system of mainly NE-SW- and NNE-SSW-oriented faults creating steep zones of weakness along which fjords and sounds are preferentially developed. The islands exhibit superb examples of the cirque glaciation, and the morphologic evidence of the processes forming the strandflat is unique in this area.
Compared to the crystalline bedrock, the sedimentary rocks of the Vestfjorden basin are considerable less resistant to erosion and were strongly affected by the action of fast-flowing ice-streams directed along Vestfjorden and turning abruptly into Trænadjupet. The extensive erosion and deposition by the ice-stream left a distinct pattern comprising a unique set of well-developed sub-glacial bedforms and moraine deposits. The cold-water Røst Reef provides another example of spectacular geology. This is the largest known reef of its kind with coral mounds occuring on the flanks of iceberg plough marks on the shelf, as well as in great concentration on the ridges in the uppermost part of the headwall zone of a giant submarine slide.
Based on the description of physiography and geology summarized here, the natural qualities of the Lofoten area appears to meet *selection criterion viii* in the sense that it exhibits outstanding examples of significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features. The extent of a possible World Heritage property should include the major physiographic and geological features described in this report.

Keywords: Geology	Geomorphology	Geophysics
Glaciers	Fjord	

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1. INTRODUCTION

This document reports the results of a feasibility study assessing whether or not the Lofoten area would qualify as a candidate for the World Heritage List based on its natural properties. The study has been undertaken by the Geological Survey of Norway based on a request from Directorate for Nature Management, Trondheim.

The potential area encompasses the following communes: Røst, Værøy, Moskenes, Flakstad, Vestvågøy and Vågan, as well as adjacent coastal areas of Vestfjorden, Trænadjupet, Røstbanken and the Ribban basin towards the shelf edge northwest of the Lofoten archipelago (Fig. 1).

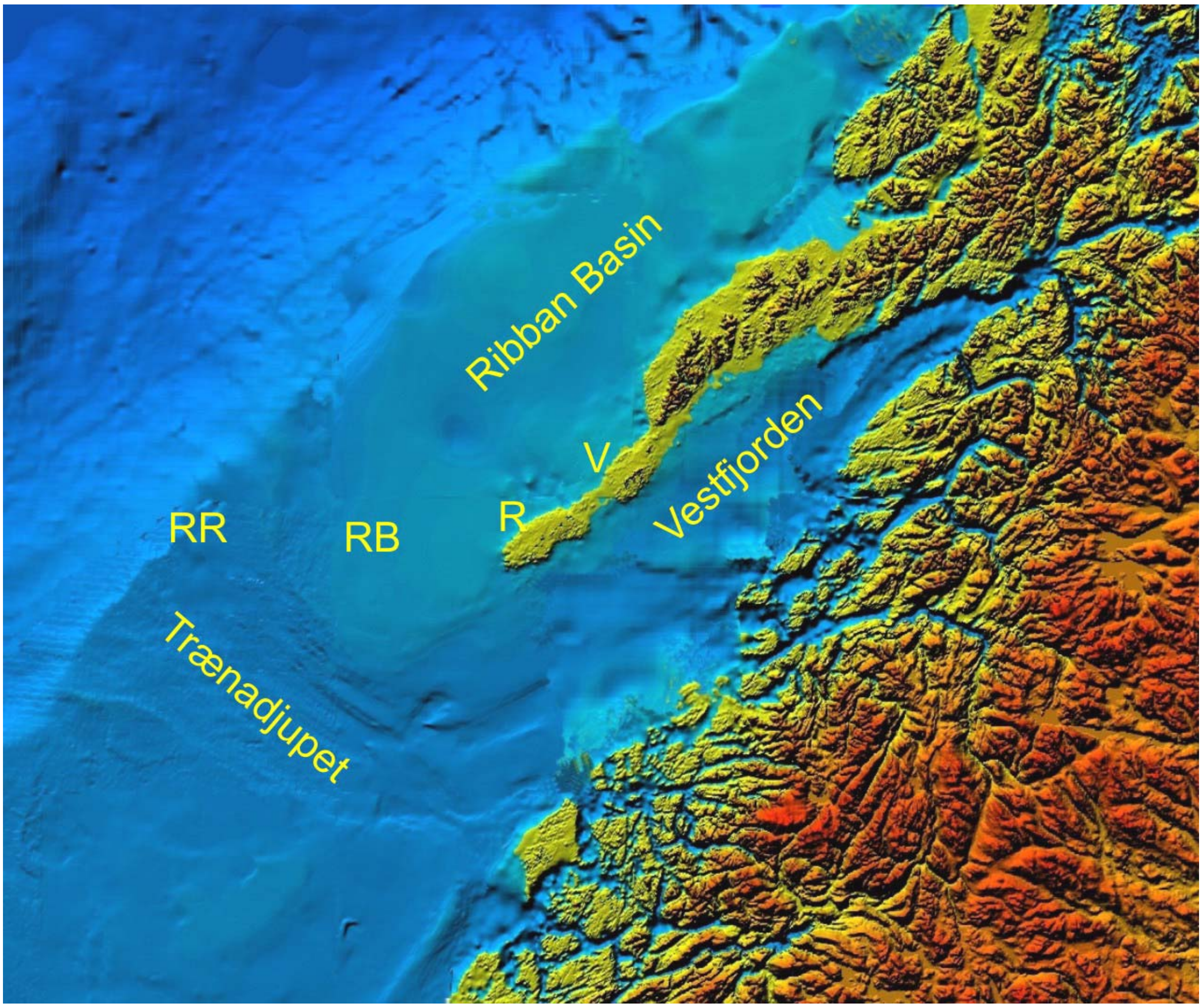

Figure 1. Combined bathymetry and topography showing the regional physiographic features of the Lofoten archipelago and adjacent areas in northern Norway. RB: Røstbanken, R: Røst, V: Værøy. RR: Røst Reef. (Figure prepared by Ole Christensen, NGU).

2. OBJECTIVE AND SCOPE

The objective of this study is to assess the potential of Lofoten as a possible World Heritage Site based on natural criteria listed in the Operational Guidelines for the Implementation of the World heritage Convention (cf. http://whc.unesco.org/en/criteria/). More specifically, we have considered whether or not the Lofoten area would have the potential to meet criterion viii, i.e. *– to be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features.*

The project has not involved detailed and systematic work. We have only given a broadly based description of the region using available geoscientific data including the general features of the landscape, and the nature of the bedrock and its structural and geophysical properties. In addition, the effects of weathering, glaciations and uplift during the Neogene and the Quaternary, and the presence of recently discovered cold-water coral reef structures are described.

The report also contains a brief analysis considering the outstanding properties of the suggested region as a whole. In relation to this, the extent of a possible property is inherently outlined to include the major physiographic and geological features described in the report.

From the description it will be apparent that a large body of geological knowledge exists from the Lofoten region. A substantial part of the report is based on results from recent and ongoing research.

3. THE LOFOTEN ISLANDS – INTRODUCTION TO THE LANDSCAPE AND REGIONAL PHYSIOGRAPHY

Lofoten comprises a series of steep mountainous islands that are heavily dissected by glacially carved cirques. The mountains are characterised by sharp peaks, some of which reach up to more than 1000 m a.s.l. Viewed from the east, the Lofoten islands appear as a continuous wall of mountains, the *Lofotveggen* – the Lofoten Wall – a 160km-long mountain ridge running from the mainland into the Norwegian Sea (Fig. 2). Steep cliffs lead directly into the sea, especially on the western and northwestern side of the islands. The strandflat is generally submerged, but is locally exposed as a narrow and discontinuous rim along the islands (Fig. 3).

Figure 2. The 'Lofoten Wall' viewed from Ulvsvåg (Hamarøy) across Vestfjorden. Photo: Terje H. Bargel.

Figure 3. Typical Lofoten landscape with steep and heavily weathered and eroded mountains, cirques, scree deposits and a narrow strandflat. View of Fredvang, Moskenesøya, in the foreground and Ramberg, Flakstadøya, in the background. Photo: Terje H. Bargel.

Austvågøya is the largest of the Lofoten islands and is dissected by several cirque valleys and cirque fjords that almost divide the island into three parts. The highest mountain is 1161 m a.s.l.; the highest peak in Lofoten. The sounds between the islands are generally narrow and shallow, and most of them are oriented N-S to NE-SW, as are most of the small fjords. The continental shelf outside Lofoten is mostly less than 200 m deep and 80-90 km wide (Holtedahl 1998). Vestfjorden, on the eastern side of Lofoten is very broad and shallow, especially at the outer part where the depth is less than 300 m. However, Vestfjorden is over-deepened, as with most of the Norwegian fjords, and reaches a depth of 627 m at its inner end.

4. BEDROCK GEOLOGY AND GEOPHYSICS

4.1 The origin of the crust in Lofoten

The Precambrian basement of the Lofoten and Vesterålen islands constitute a NNE-trending basement high characterized by anomalously thin continental crust on the North Atlantic margin. The basement rocks continue to the northeast into western Troms and are overlain to the east by a stack of allochthonous Caledonian nappes occupying the central axis of the Scandinavian Caledonides (Fig. 4). Based on geological relationships supported by the regional scale magnetic anomaly patterns, it has been suggested that the Lofoten–Vesterålen basement is directly linked to the Baltic Shield below the nappes (Griffin et al. 1978, Griffin & Taylor 1978, Tveten 1978, Gustavson & Blystad 1995, Olesen et al. 1997).

The Lofoten islands consist mainly of Palaeoproterozoic rocks. Immediately to the northeast of the proposed area, Archaean rocks including tonalitic gneisses and minor greenstone belts older than 2500 Ma (Ma = million years is used throughout this report) occupy large parts of the islands of Langøy and Hinnøy. Small remnants of Archaean rocks may also be present at the southwestern tip of Austvågøy (Wade 1985). A younger sequence of Palaeoproterozoic paragneisses that occur throughout Lofoten is composed mainly of quartz-feldspar-rich gneisses with subordinate graphite schist, iron formations and marble. The suggested age of these rocks (ca. 2100 Ma) is uncertain, but they have gone through a similar type of high-grade metamorphism as the Archaean migmatites to the northeast.

The Archaean rocks and the Palaeoproterozoic supracrustal sequences have been intruded by plutons that occupy more than 50% of the Lofoten islands (Fig. 4). A series of age determination carried out on a set of widely distributed, representative rocks show that the bulk of these plutons were emplaced during a fairly short time period at 1800-1790 Ma (Corfu 2004a). The nature and composition of the plutons belong to the so-called anorthosite–mangerite–charnockite–granite (AMCG) suite that are typical of Proterozoic crust (Malm & Ormaasen 1978). Charnockites and mangerites dominate and form a series of large plutons, e.g. the Raftsund, Hopen, Sund–Ølkona and SW Lofoten intrusions. Small plutons (<50 km^2) of gabbro and anorthosite are scattered throughout the islands. Petrological studies and isotope data suggest that the majority of the Lofoten intrusive rocks can be modelled as a mixture of 1) 1800 Ma mantle-derived melts that represent juvenile additions to the crust, and 2) Archaean lower crustal material (Markl & Höhndorf 2003, and references therein).

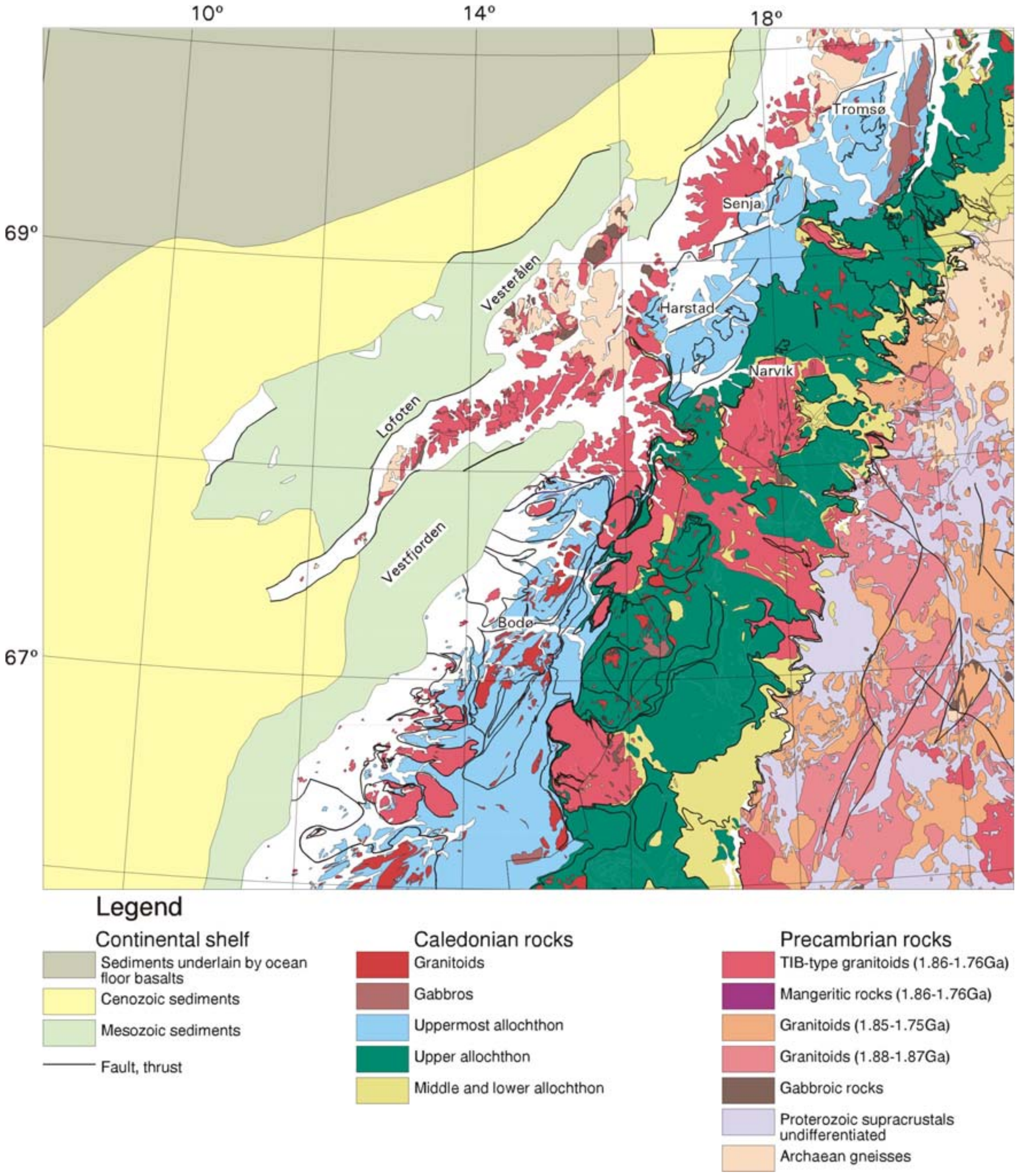

Figure 4. Simplified bedrock map of Lofoten and adjacent areas of northern Fennoscandia, showing the regional distribution of major rock units. Lofoten consists of Precambrian rocks forming the westernmost part of the Fennoscandian Shield emerging from below the Caledonian allochthonous rocks. Lofoten is the only exposed basement high on the North Atlantic continental margin. Adapted from Koistinen et al. (2001); the map was prepared by Arne Solli, NGU.

4.2 The Caledonian event

The Caledonian mountain belt extends through western Scandinavia. During the Silurian and Early Devonian continent-continent collision between Laurentia (Greenland and North America) and Eurasia (ca 400 – 450 Ma ago), far-travelled thrust sheets were emplaced from the northwest onto the Precambrian basement of Fennoscandia (Fig. 4). In the Lofoten islands, the Leknes Group forms an exotic element of Caledonian rocks (Klein et al. 1999; Corfu 2004b). It consists of amphibolite-grade paragneisses and schists that tectonically overlie the Palaeoproterozoic basement on western Vestvågøy. Recent work has shown that it was subjected to polyphase deformation and metamorphism during the Caledonian orogeny (Steltenpohl et al. 2003; Corfu 2004b).

The effects of the Caledonian orogeny are expressed by eclogites that occur in shear zones in the granulite-facies basement in Lofoten (Wade 1985). The elogites were previously interpreted as having formed during the Proterozoic with minimum conditions during eclogite formation of 540–680 ºC and 14–15 kbar (Markl & Bucher 1997). Recent Ar-Ar age determinations, however, show that the eclogites most likely formed during the Caledonian event (Steltenpohl et al. 2003). These data show that the rocks exposed at the surface today were located at lower crustal depths (ca 45 km) prior to late- and post-Caledonian extensional events and exhumation of the crustal section in Lofoten.

4.3 Crustal thinning and exhumation of deep crustal rocks

The initial post-Caledonian exhumation of the Lofoten deep-crustal rocks has lately been related to core complex formation and denudated during large-magnitude extension along major detachment faults during the Devonian and Carboniferous (Løseth & Tveten 1996, Hames & Andresen 1996; Braathen et al. 2000). During the subsequent Mesozoic and Cenozoic rifting events (Løseth & Tveten 1996), including the opening of the North Atlantic beginning in the Early Tertiary (ca 55 Ma), stretching and normal faulting caused further thinning of the crust below Lofoten to its present thickness of ca 20 km (Fig. 5). Exhumation of the crust caused a drop in temperatures, and in the Jurassic a peneplained erosion surface had developed in the area. Normal faulting and renewed subsidence and deposition of sediments initiated in the Mid Jurassic and continued into the Cretaceous. Large fault movements led to the development of Lofoten as a horst in the Early Cretaceous, and a several kilometre thick Lower Cretaceous succession was deposited in surrounding basins. Minor faulting along Lofoten also took place during the final rift phase in the Early Tertiary.

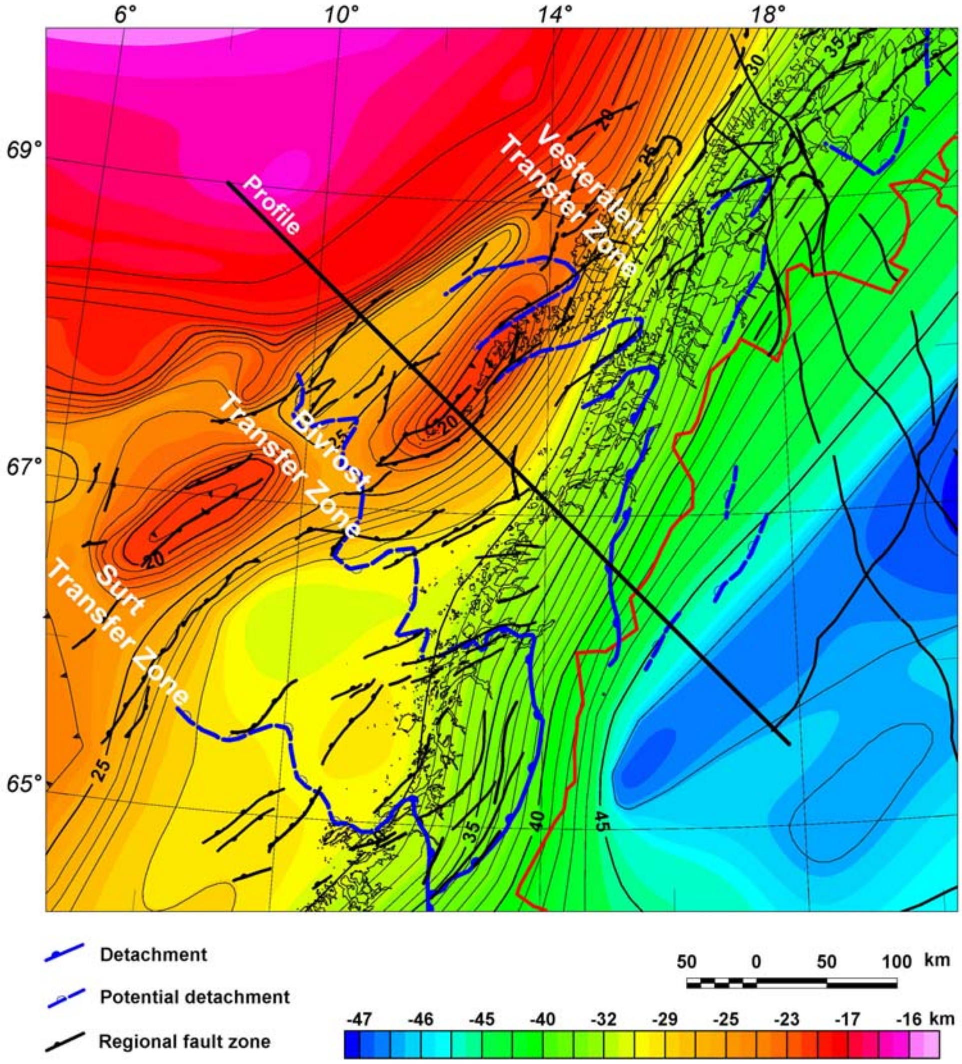

Figure 5. Depth to Moho compiled from refraction seismic and gravity studies (Olesen et al. 2002). The black line crossing the outer Lofoten islands shows the location of the interpreted geophysical profile (Fig. 6). The shallow Moho occurs below the main Late Jurassic - Early Cretaceous rift axis including the Lofoten islands. The shallow Moho bulge is deflected by the Surt, Bivrost and Vesterålen transfer zones. Note: Moho is the geophysically defined boundary between the crust and the underlying mantle.

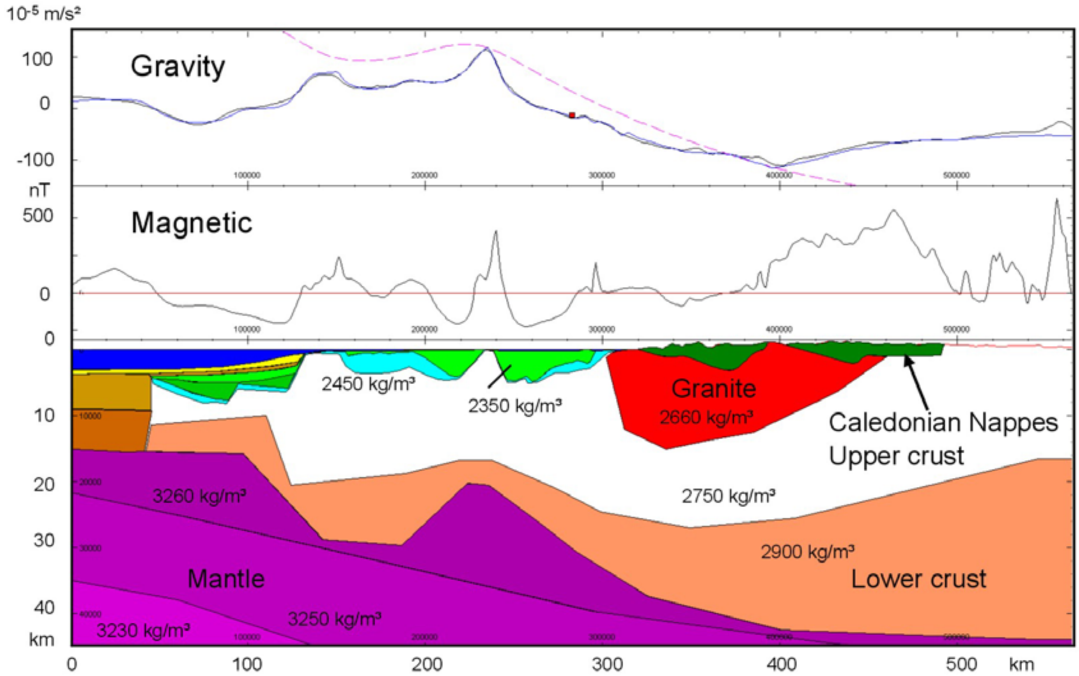

Figure 6. Cross section through the Lofoten area (Olesen et al. 2002); see Fig. 5 for location. Sedimentary succession: yellow - Tertiary, brown - Tertiary flow basalts and oceanic crust, light green – Upper Cretaceous, green – Lower Cretaceous, blue – Pre-Cretaceous, pale pink – pre-Jurassic; dark green – Caledonian Nappes. The black lines show the observed gravity and magnetic fields while the blue lines illustrate the gravity response of the total 3D model. The dashed purple line represents the regional gravity response from the mantle.

At present, the archipelago represents the footwall block of extensional faults facing the adjacent Vestfjorden and Ribban sedimentary basins (Fig. 6). The rifting has thus produced a shallow, high-density mantle and caused uplift of the deep crustal rocks exposed at the surface. This also explains the anomalous gravity high in the region (Fig. 7). The rifting events have in addition resulted in uplifted and rotated fault-blocks separated by local transfer zones. These structural elements can be recognised in the present day topography (Bergh et al. in prep.). The prominent Bivrost and Vesterålen transfer zones (Fig. 5) coincide with regional changes in Moho depth and are consequently deep-seated crustal features, strongly influencing the segmentation of the rift. Moho bulges occur therefore in the Lofoten-Vesterålen area and below the Utgard High/Træna Basin (Fig. 5).

Riis (1996) and Hendriks & Andriessen (2002) have proposed a Neogene bedrock uplift of more than 1000 m in the Lofoten-Vesterålen area from extrapolation of the offshore Late Tertiary stratigraphy and apatite fission track data, respectively.

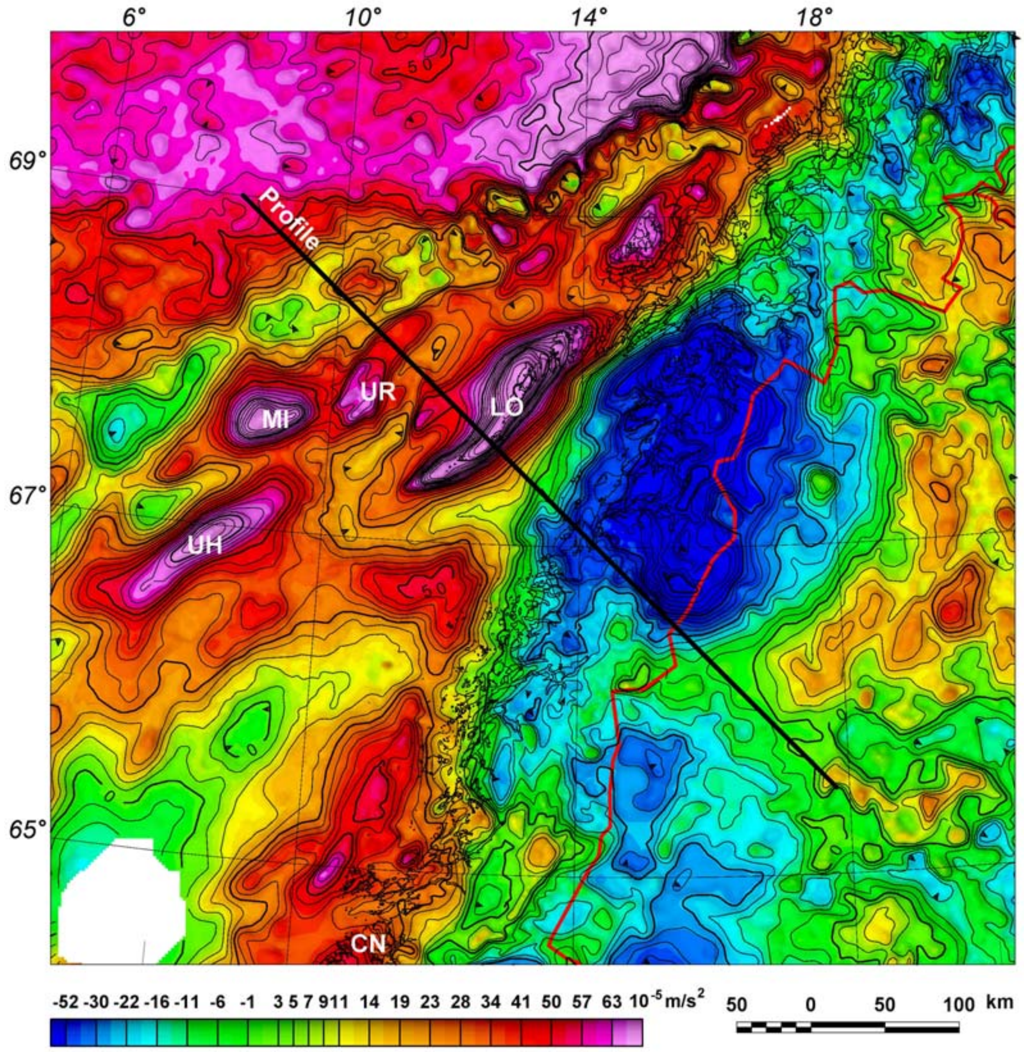

Figure 7. Residual gravity after isostatic correction of Bouguer gravity data. (Olesen et al. 2002). The Lofoten Archipelago coincides with a gravity high caused by a shallow Moho and exhumed high grade metamorphic rocks from the lower crust. The black line shows the location of the interpreted profile in Fig. 6.
CN - Central Norway basement window; LO - Lofoten Ridge; MI - Myken intrusive complex; UH - Utgard High; UR - Utrøst Ridge.

To summarize, a shallow Moho underlies the Late Jurassic to Early Cretaceous rift axis, consisting of the adjacent Træna, Ribban, Vestfjorden and Harstad basins. The Lofoten archipelago constitutes an integrated part of the Norwegian continental shelf that has been uplifted during several tectonic phases. The final 1000 metres of uplift occurred during the last 10 million years (Neogene period), leaving lower-crustal rocks dissected by major faults exposed at the surface. Compared to the sedimentary rocks adjacent to it, the Precambrian rocks along Lofoten are highly resistant to erosion. Although they were substantially modified, the chain of mountainous islands persisted during extended periods of severe glacial conditions. It is the exceptional combination of tectonic events and subsequent glacial erosion and weathering that has produced the unique geological setting and the stunning landscape of the Lofoten archipelago.

5. QUATERNARY GEOLOGY OF THE LOFOTEN ISLANDS

5.1 Glacial deposits and weathering products

Quaternary deposits are generally sparse in Lofoten. Weathering material occupies extensive areas as autochthonous blankets of varying thickness, or as talus fans or aprons beneath the numerous steep cliffs (Bargel 2001) (Fig. 8, Fig. 9). The granites, monzonites and schists appear to be the rock types most susceptible to weathering.

Figure 8. The weathering processes and accompanying scree deposits are characteristic of many parts of Lofoten. Very little till is present. From Kongsjord, southern Vestvågøya. Photo: Terje H. Bargel.

Thick deposits of till have been identified at several localities, but probably due to the weathering and periglacial processes (soil creep, stone upheaval, etc.), the till is generally difficult to differentiate from weathering material. Erratics are observed close to the highest peaks on most of the islands. Grønlie (1940) and Bergström (1973) interpreted the erratics as proof of complete ice cover during the Weichsel Late Glacial Maximum (LGM). However, local deep weathering suggests that large areas of the mountainous islands were not covered by glaciers, or possibly existed as nunataks protruding from a local ice dome during successive glacial periods. Ice-free mountains during the last glaciation have also been proposed based on cosmogenic dating (Dahl 2004). Recent studies of ice-stream dynamics supports this view, indicating the former existence of an efficient ice drainage from the central parts of the Fennoscandian Ice Sheet into Vestfjorden, south and east of Lofoten, and into Andfjorden north and east of the archipelago (Ottesen et al. 2005a,b).

As already noted by Keilhau (1838) and Helland (1897), most of the moraines are located in the short Lofoten valleys (i.e., cirque valleys). Vogt (1907) described several moraines that he claimed were a result of local glaciation. During the previous century, several models were presented to explain aspects of glacial deposits and possible consequences for the deglaciation history of the region (for a summary, see Bargel 2003).

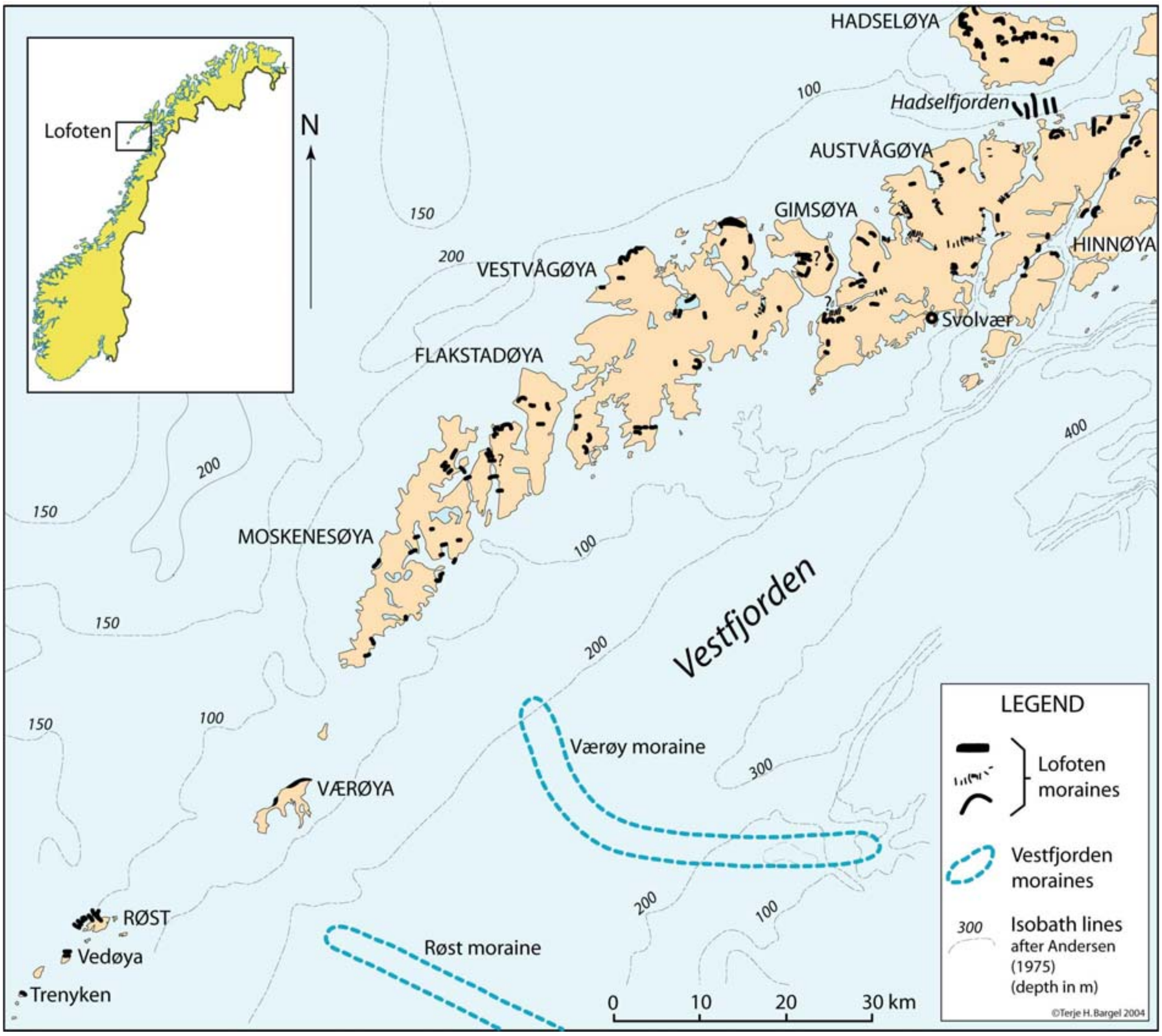

Figure 9. Sketch map of the Lofoten islands showing the distribution of moraines. The map from is from Bargel (2003).

In a recent study, Bargel (2003) described and classified the moraine deposits occurring throughout the Lofoten archipelago (cf. Fig. 9) and presented a revised history of deglaciation for the region. The various moraines were related to events in the local deglaciation history starting ca 15 ka ago. Cirque moraines were shown to be the youngest and most frequent type.

They are probably related to the Younger Dryas and the Preboreal climatic deteriorations (10-11 ka BP and 10-9 ka BP, respectively). The effects of the local glaciers have had a profound effect on the landscape (see below).

5.2 The strandflat and near-shore submarine landscape

The Quaternary, with its changing climate and repeated ice ages, has had a major impact on the morphology of the Lofoten area, both onshore and offshore. The strandflat (Reusch 1894, Nansen1904, Holtedahl 1998) – a rock platform at ± 40 m around the present sea level – is well developed around Røst and Værøy and on the north west side of the main Lofoten islands (Fig. 10). This platform is a Quaternary morphologic element developed by frost activity at sea level, marine abrasion and cirque glaciers, and modified by regional glacial erosion (Holtedahl 1998). Lofoten is situated ca 60 km from the shelf break, with Vestfjorden forming a wide embayment separating the islands from the mainland.

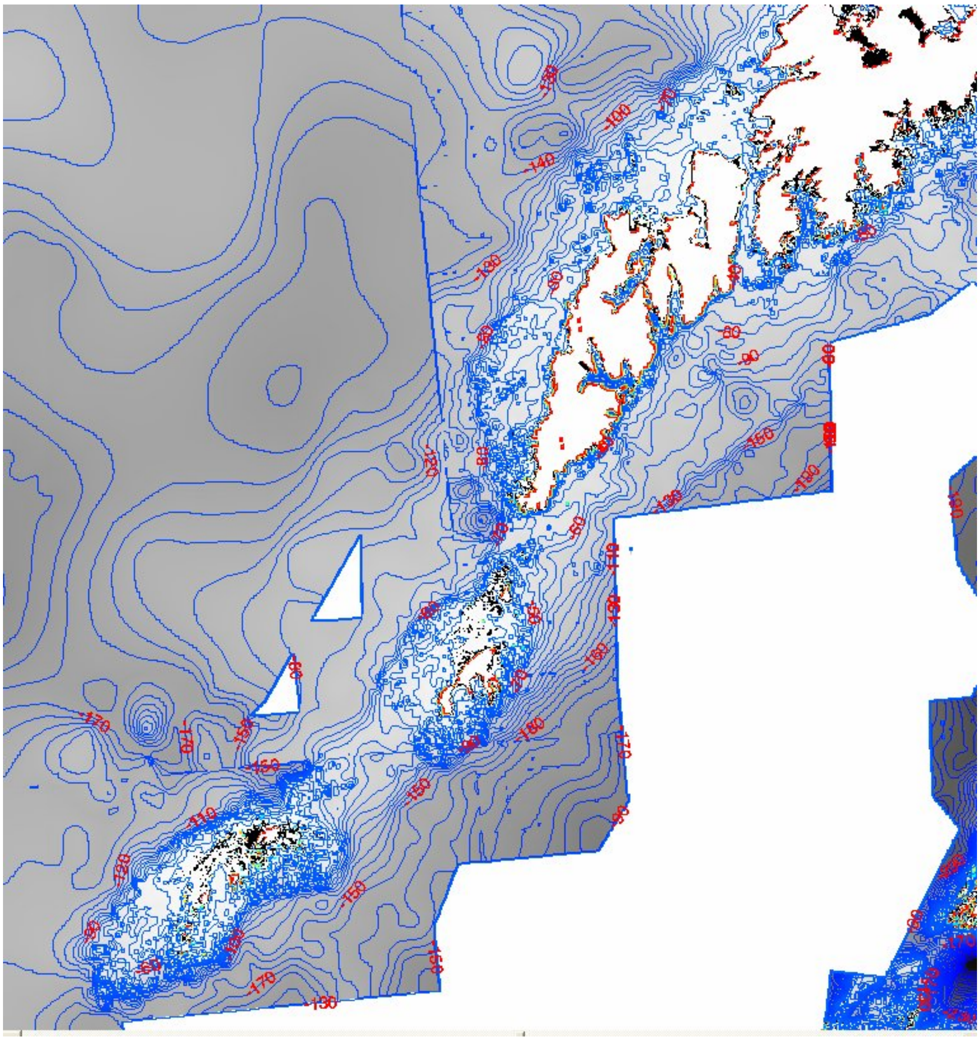

Figure 10. Detailed bathymetric map showing the prominent development of the strandflat to the northwest of the outermost Lofoten islands, including the Værøy and Røst archipelagoes.

Ice streams draining the inland ice caps during major glaciations partly isolated the islands from the inland ice, and local ice caps were formed. The short distance to the shelf break drained the local ice caps effectively and prevented them to grow large. Therefore, the mountains have been nunatacs or hosted cirque glaciers for long periods during the Quaternary. An excellent example of the effects of local glaciers is the island Austvågøy, the largest of the Lofoten islands, which is dissected by several cirque valleys and cirque fjords that almost divide the island into three parts. Superb example of the cirque glaciation is also found on the island Moskenesøy. The island has a pock-scarred surface where cirques form local, deep inlets into the crystalline rocks of the mountainous island. On the shelf surrounding the island, in the direction towards Værøy and Røst, bathymric data show that similar depressions are present. This demonstrates that the subaerial part of the cirques has been removed, while local, enclosed depressions are still preserved on the sea floor. The modification and partial removal of the glacially carved cirques occurred mainly through frost activity and marine abrasion at sea level during ice-free periods, leaving 'rest mountains' with steep slopes rising from the strandflat (Fig. 3). At Værøy, the peaks reach up to 450 m above sea level, whereas at Røst most of the mountains have been removed. The very distinct morphologic evidence of the processes forming the strandflat is unique in this area and well expressed by the near-shore bathymetry.

5.3 The ice-stream systems in the Vestfjorden basin and Trænadjupet

Regional and detailed bathymetric data from Vestfjorden and Trænadjupet that significantly improves our understanding of the glacial history of the region, have recently been published by Ottesen et al. (2005b) and Dowdeswell et al. (in press). Vestfjorden forms an NE-SW-trending 250 km long embayment that narrows towards the northeast. Its origin as a sedimentary basin differs in many fundamental ways from that of the classic, narrow fjords in western Norway. Water depths in the innermost narrow parts reach 600 m. Southwestwards the 'fjord' widens and shallows, and off Værøy the water depth is 200–300 m and the width is 50–60 km. In outer Vestfjorden, the water depth increases to 350–400 m. At the head of Vestfjorden there is a system of narrow, over-deepened fjords; e.g. the E–W-trending Ofotfjorden, which is up to 550 m deep and ca. 70 km long, and the N–S-trending, 900 m deep Tysfjorden. Vestfjorden terminates against Trænadjupet; a NW-SE-trending, 150 km long and up to 500 m deep trough that crosses the shelf southwest of Røstbanken, representing the continuation of Vestfjorden to the shelf edge (Fig. 11). The location of Trænadjupet approximately coincides with the Bivrost Transfer Zone (Fig. 5)

Bathymetry data and marine-geophysical datasets aquired from Vestfjorden and Trænadjupet (Ottesen et al. 2005b) reveal a number of spectacular features that reflect processes and conditions during past ice stream flow (Figs. 11-13):

- glacially-eroded troughs,
- streamlined glacial lineations,
- longitudinal ridges,
- transverse morainal ridges.

The high mountains of the Lofoten islands and on the mainland to the east of Vestfjorden had an important influence on regional ice flow in the area, and major ice streams have been directed along Vestfjorden during several glacial periods. Prior to the most recent glacial period (Weichselian), the ice streams were directed from Vestfjorden southwestwards towards the continental margin off mid Norway. Following a dramatic shift in the ice-flow direction, the ice stream during the LGM (ca 20000 years ago) made an abrupt 90º turn from Vestfjorden into Trænadjupet. A complex system of tributaries from the inland Fennoscandian Ice Sheet provided supply for the ice stream that flowed along Vestfjorden. Ice streams emerging from the fjords on the mainland flowed towards the northwest and were quite abruptly deflected towards the southwest, providing additional supply for the major ice stream that continued into Trænadjupet and further towards the shelf break (Fig. 11). Ice from the Lofoten islands may also have drained into the main ice stream along Vestfjorden. The ice stream eroded substantially into the thick glacial units and subjacent sedimentary bedrock in Trænadjupet. For the entire ice drainage system (Vestfjorden and Trænadjupet), Ottesen et al. (2005b) estimated a total ice-sheet drainage area of up to 150,000 km^2. Using available information, they calculated an average ice-flow velocity of 750 m/year.

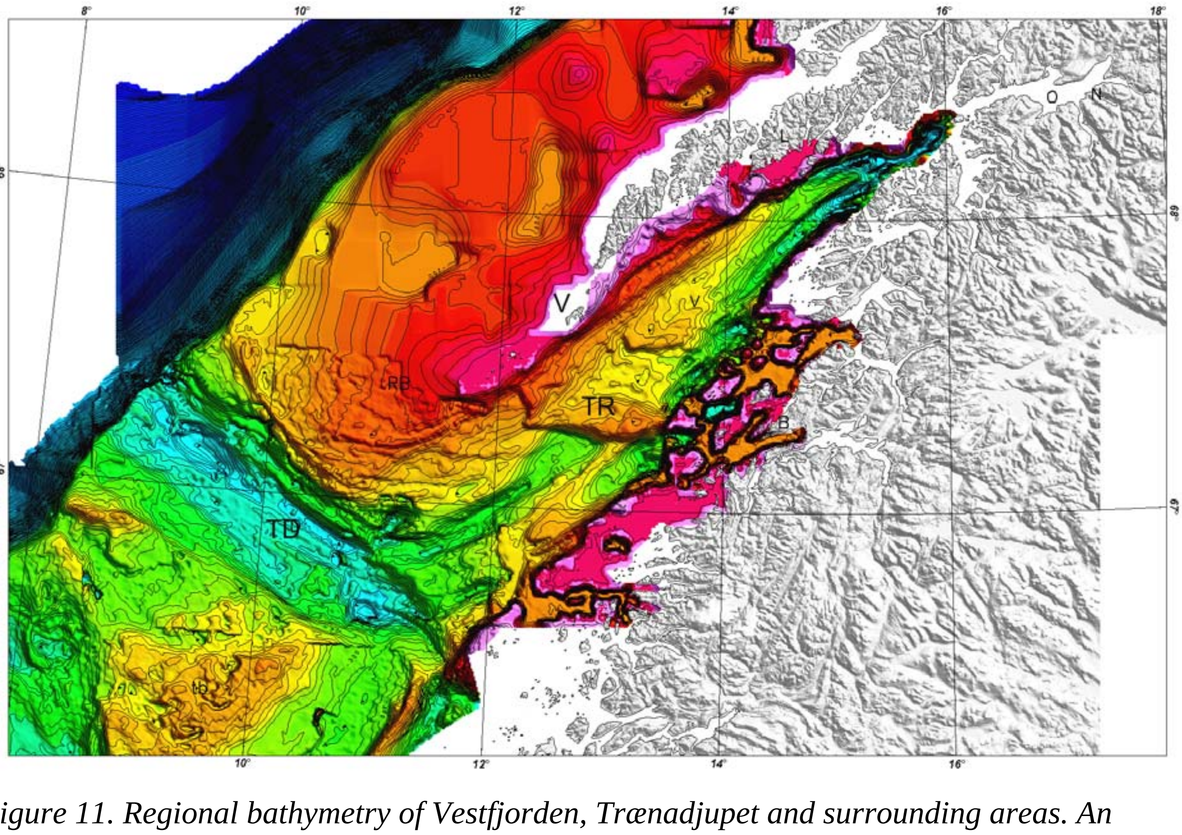

Figure 11. Regional bathymetry of Vestfjorden, Trænadjupet and surrounding areas. An elongate, 600m deep trough eroded by the ice-stream is present in the innermost part of Vestfjorden. Elongate troughs are also developed in Trænadjupet (TD). Black arrows point to examples of longitudinal ridges representing ice-stream shear margin moraines that are present on both sides of Trænadjupet. The Tennholmen Ridge (TR) is a major transverse morainal ridge across Vestfjorden. V: Værøy. Adapted from Ottesen et al. (2005b).

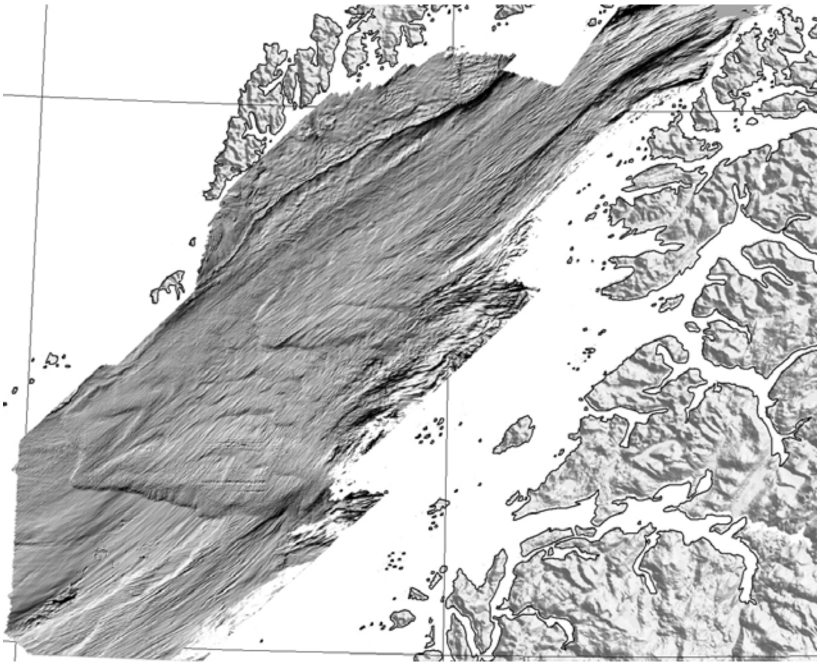

Figure 12. Shaded relief image of the sea-floor of Vestfjorden from multibeam bathymetry. The prominent Tennholmen Ridge crosses the outer part of the fjord (cf Fig. 11) The figure provides a detailed picture of the glacial lineaments parallel to the trough axis in Vestfjorden. Note the tributary ice-flow systems that derive from the fjords on the mainland; these are deflected and merge with the main ice-stream in Vestfjorden. Adapted from Ottesen et al. (2005b).

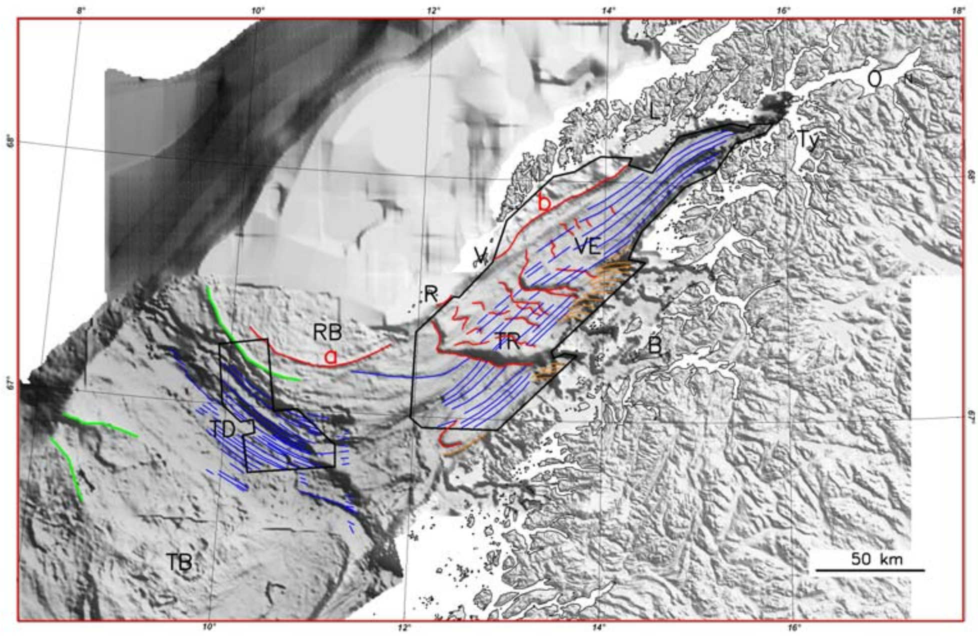

Figure 13. Sub-glacial landforms resulting from the ice-stream in Vestfjorden and Trænadjupet (Ottesen et al. 2005b). Green lines: ice-stream – ice-stream shear margin moraines; blue lines: mega-scale glacial lineations; orange lines: drumlins; red line: transverse moraine ridge.

5.4 The Røst Reef – the world's largest deep-water coral reef

The use of multibeam echosounders, together with advanced visualisation and analysis tools has been a key to many spectacular discoveries of cold-water coral reefs, notably the stone coral *Lophelia pertusa* that has been extensively found in deep Arctic waters, such as the Norwegian Sea. In 2002, the world's largest cold-water coral reef – the Røst Reef – was discovered and mapped in detail (Thorsnes et al. 2003; Fig. 14).

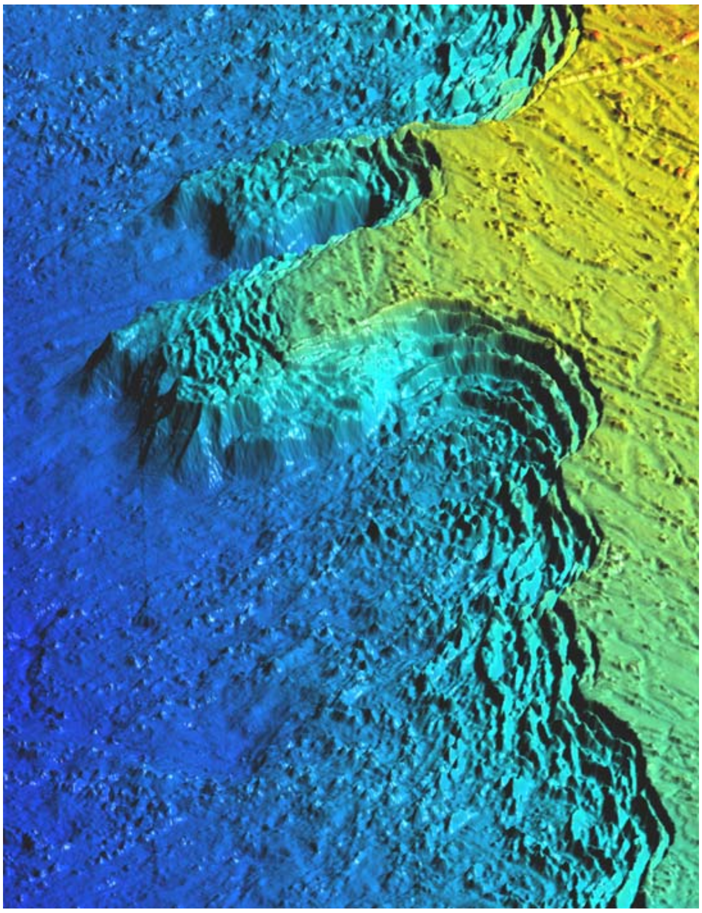

Figure 14. 3D model of the central part of the Røst Reef, showing a major submarine slide that has created a dramatic landscape, with chaotic and steeply dipping fault blocks. The reef complex covers both the shelf part with water depths of ca. 290 m below sea level, and the uppermost part of the headwall zone. (Thorsnes et al. 2003).

The geological setting of this reef complex is spectacular – situated along the headwall of a giant submarine slide, the Trænadjupet slide (Fig. 14), located near the northwest end of Trænadjupet (Fig. 1). According to scientists at the University of Tromsø, the slide took place about 4000 years ago. Steep, dissected ridges that are several tens of meters high occur in an up to 2 km wide headwall zone seaward from the shelf break. Abundant coral mounds occur on the flanks of iceberg plough marks on the shelf (Fig. 14), however, the largest concentration is found on the ridges in the uppermost part of the headwall zone.

6. SUMMARY

The geology of the Lofoten region has been described to assess whether or not the area would qualify as a candidate for the World Heritage List based on its natural properties.

The Lofoten archipelago consists mainly of Palaeoproterozoic rocks, including paragneisses and younger plutons (ca 1800 Ma) of the anorthosite–mangerite–charnockite–granite (AMCG) suite. The Precambrian basement of the Lofoten and the adjoining Vesterålen islands is part of a NNE-trending basement high that is overlain to the east by a stack of allochthonous nappes occupying the central axis of the Scandinavian Caledonides.

During Caledonian continent-continent collision, the rocks exposed at the surface today were situated at considerable depth in the crust (ca 45 km). Late- and post-Caledonian extension and exhumation of the crustal section, and the following Mesozoic rifting events resulted in a highly attenuated crust (<20 km) over a shallow Moho. The Lofoten archipelago developed as a protruding basement ridge (horst) forming a part of the Norwegian continental shelf that was uplifted during several tectonic phases during development of the NE Atlantic margin. The final 1000 metres of uplift occurred during the last 10 million years (Neogene period), leaving lower-crustal rocks dissected by major faults exposed at the surface.

The unique setting of Lofoten as an exposed ridge of lower crustal rocks forming a basement high on a highly extended continental margin is a result of an exceptional combination of tectonic events and subsequent glacial erosion and weathering. Apart from its breathtaking landscape, the well-exposed Lofoten archipelago provides an exceptional possibility to study the effects of past and present geological processes.

The Precambrian rocks along Lofoten are highly resistant to erosion. Although they were substantially modified, the chain of mountainous islands persisted during extended periods of severe glacial conditions. The present 'Alpine' landforms are governed by a system of mainly NE-SW- and NNE-SSW-oriented faults creating steep zones of weakness along which fjords and sounds are preferentially developed. The islands exhibit superb examples of the cirque glaciation, and the morphologic evidence of the processes forming the strandflat is unique in this area. The connection between the geological processes and their morphological results are thus manifest both in the large-sale as well as the local physiographic features.

Compared to the crystalline bedrock, the sedimentary rocks of the Vestfjorden basin are considerable less resistant to erosion and were strongly affected by the action of fast-flowing ice-streams directed along Vestfjorden and Trænadjupet. The extensive erosion and deposition by the ice-stream left a distinct pattern comprising a unique set of well-developed, large-scale, sub-glacial bedforms and moraine deposits. Based on the orientation of the glacial landforms, the flow direction of the ice stream changed dramatically prior to the onset of the Last Glacial

Maximum. Fast-flowing ice streams are temporally common from the Greenland and Antarctic ice sheets. However, the major shift in the direction of the deep ice stream as inferred from the Vestfjorden-Trænadjupet ice-stream system, has as yet not been observed in any of these settings.

The cold-water Røst Reef provides another example of spectacular geology. This is the largest known reef of its kind with coral mounds occurring on the flanks of iceberg plough marks on the shelf, as well as in great concentration on the ridges in the uppermost part of the backwall zone giant submarine slide.

Based on the description of physiography and geology summarized in this report, the Lofoten area appears to meet *selection criterion viii* in the sense that it exhibits outstanding examples of significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features. With respect to the extent and integrity of a potential property, the island areas would need to be considered with respect to former or current exploitation of resources that may have caused changes to the landscape and/or disturbance of ongoing geological processes. For the offshore areas, one would need to find a way to incorporate features of the submarine landforms that are representative of the wide range of geological processes that have operated during the formation of the landscape. This would include the near-shore and submarine cirques and strandflat, the wide variety of sub-glacial bedforms and moraine deposits resulting from major ice streams, and the Røst Reef and adjacent areas.

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